CHEMICAL ENGINEERING TRANSACTIONS

VOL. 77, 2019

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977162

Explosion Mitigation using Aqueous Solutions of Water and Flame Inhibitors

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The current paper describes results of tests performed with aqueous solutions of flame inhibitors at a larger-scale. Two sets of experiments were performed: experiments using superheated aqueous solutions and experiments where aqueous solutions were dispersed using a water deluge system. The main aim of these experiments was to verify the effects seen on small-scale on a larger scale to verify the possibility of using this mitigation technique on industrial scale. Both sets of experiments were performed in a congested 50m^3 chamber provided with explosion venting. To generate water-mists directly at a larger-scale in sufficiently high concentrations a dispersion of superheated aqueous solutions of potassium carbonate seems to be the only viable solution. The application of a water deluge system implies relying on break-up of the large water droplets by the accelerating explosion flame itself.

1. Introduction

Vapour cloud explosions are among those events causing the highest losses in the petrochemical industry. Research in the past has especially been devoted to predicting the consequences of these events. Obviously, preventive measures is given high attention to prevent these incidents from happening including correct design of the facilities, its maintenance and inspection and choice of equipment approved for use in potentially explosive atmospheres. Less attention has been given to mitigation of vapour cloud explosions, i.e. limitation of consequences.

Especially for offshore applications water deluge has been shown to be effective as a means of explosion mitigation. The water deluge system shall be activated before ignition. The positive impact of water deluge has been documented extensively (Catlin et al., 1993, van Wingerden, 2000). It has been demonstrated that only droplets smaller than 10-20 μm will affect flame propagation due to evaporation in the flame (in methane-air mixtures). Larger droplets need to break-up before having an impact. Hydrodynamic forces acting on droplets in an accelerating flow will allow droplets to break up if these droplets are not able to adapt to the flow accelerations. Flow accelerations occurring during explosions in congested areas are able to break-up droplets larger than typically 200 μm (Van Wingerden, 2000).

Hoorelbeke (2011) suggested to use solid flame inhibitors dispersed into the vapour cloud upon its release as an alternative mitigation technology. This technology has shown to be effective and has even been tested on full scale showing its potential (Davis et al., 2017). Relatively low concentrations (50-100 g/m^3) of solid flame inhibitors such as sodium bicarbonate, sodium chloride, potassium carbonate and potassium bicarbonate are able to reduce flame speeds and overpressures in hydrocarbon-air mixture explosions considerably (Van Wingerden et al, 2011).

Roosendans et al. (2017) suggested to investigate the possibility of combining the two: applying aqueous solutions of flame inhibitors to mitigate vapour cloud explosion. Experimental investigations were performed on small-scale using water mist-potassium carbonate solutions. Whereas water mist alone already had an impact and caused a reduction of flame speeds and overpressure introducing potassium carbonate in the water resulted in an additional reduction. The experimental results show that by increasing the amount of

Paper Received: 28 December 2018; Revised: 17 May 2019; Accepted: 29 June 2019

Please cite this article as: van Wingerden K., Holme M., Olsen K., Roosendans D., Hoorelbeke P., 2019, Explosion mitigation using aqueous solutions of water and flame inhibitors, Chemical Engineering Transactions, 77, 967-972 DOI:10.3303/CET1977162

potassium carbonate an increase of the degree of mitigation is observed up to full quenching of the explosion flame. An example of typical results obtained are summarised in Figure 1. Water concentrations between 30 – 80 g/m^3 were used.

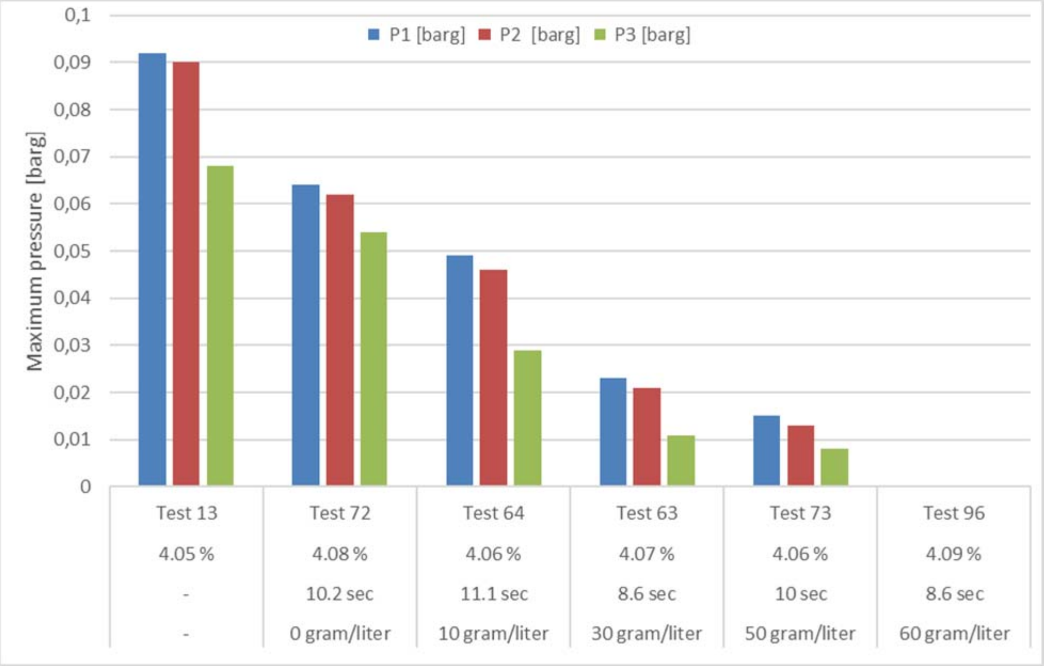

Figure 1: Effect of aqueous solutions of potassium carbonate on explosion overpressures in 4.05-4.09 % propane-air mixtures in a 0.135 m^3 channel with baffles. Overpressures are measured at 3 locations for increasing amounts of the flame inhibitor dissolved in water (increasing from 0 to 60 g/litre). Water mist concentration is determined by the injection duration varying from 8.6 to 11.1 s.

2. Description of the test set-up

Both series of tests were performed in a congested chamber 8.0 m long, 2.5 m high and 2.5 m wide, thus having a volume of 50.0 m³. The chamber has a coarse steel grating forming a mezzanine deck approximately 1.25 m above the floor of the vessel. Three of the walls of the chamber can be used as vent openings. As Figure 2 shows the chambers contains several objects (obstructions) which cause explosion flames to accelerate due to turbulence generated at these obstructions. Ignition was effected using an exploding wire located close to one of the short walls of the chamber (1 m from the end in the centre).

The tests to investigate the effect of superheated aqueous inhibitor solutions were performed having both short ends of the chamber opened. The water deluge tests were performed having only 1 short end opened. The ignition end was chosen to be the closed end of the chamber.

The superheated aqueous solutions were introduced into the explosion chamber from three 4 litre suppression bottles supplied by IEP Technologies UK. Each bottle was connected to a nozzle and mounted along the centre line of the roof of the explosion chamber, regularly divided. The bottles were either filled with 2 or 3.5 litres of water or aqueous solution. The system was activated 6 s before ignition to limit turbulence generated during the injection.

The water deluge was provided from 7 to 11 nozzles of type MV12 125° with K-factor of 18.7. The nozzles were mounted regularly divided against the roof of the chamber. The total water/aqueous solution application rate was varied between 9.5 l/min/m^2 to 22 l/min/m^2.

3. Results

3.1 Superheated aqueous solutions

Initially tests were performed to investigate the effect of superheated water only on explosions in propane-air mixtures. Results obtained for 4.15 % propane-air mixtures are summarised in Figure 3 showing a clear reduction of overpressures when increasing the amount of superheated water released from 0 to 10.5 l. The

Figure 2: 50 m^3 explosion chamber used to investigate effect of aqueous of flame inhibitors

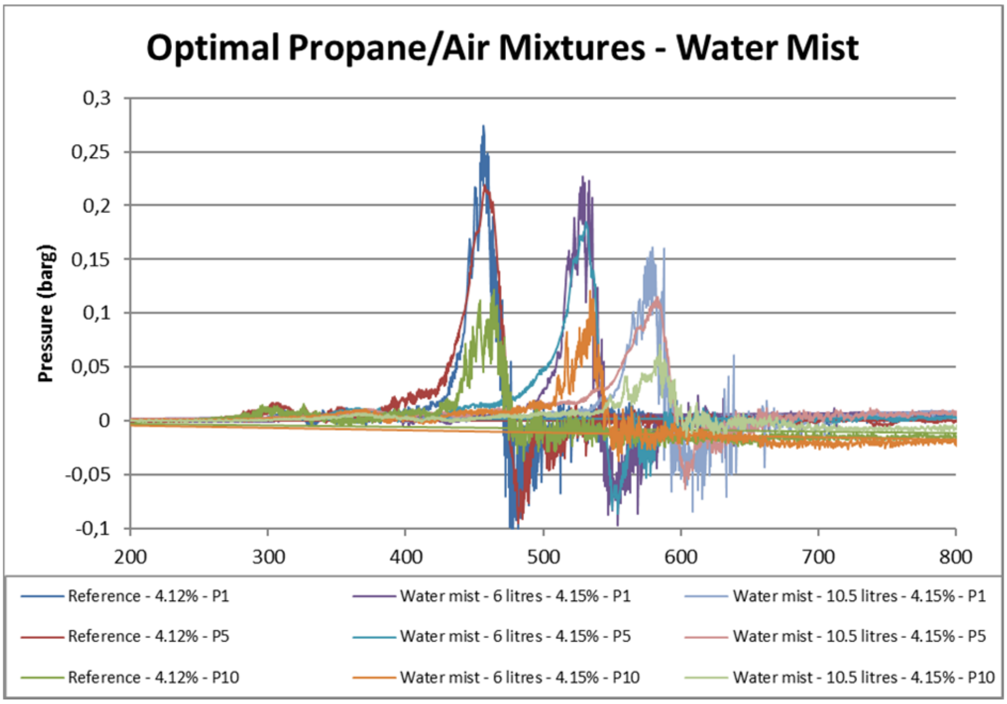

Figure 3: Effect of superheated water on overpressure generated by optimal propane-air explosions in a vented 50 m^3 obstructed chamber. The amount of water released was increased from 0 to 10.5 l.

results show that both the pressure spikes are delayed and reduced when introducing the fine water droplets indicating a reduction of the combustion rates immediately after ignition. Similar effects were seen when introducing superheated water into both lean and rich propane-air mixtures.

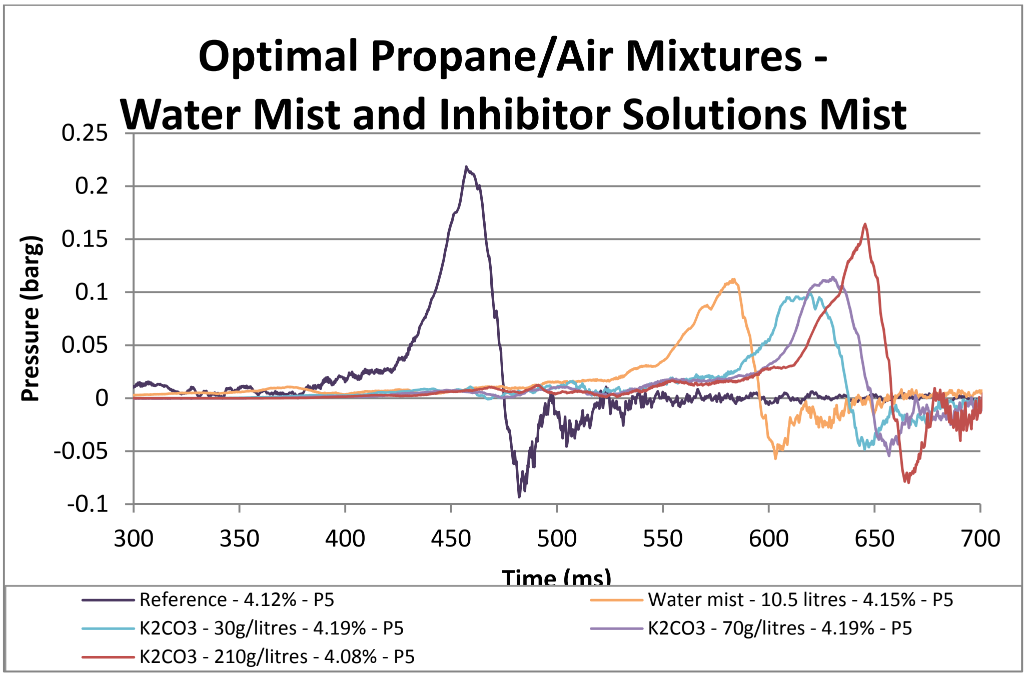

Figure 4: Effect of superheated aqueous solutions of water and potassium carbonate on overpressures generated by optimal propane-air explosions in a vented 50 m^3 obstructed chamber. The amount of water released was 10.5 l. The potassium concentration in the water was increased from 0 to 210 g/l.

Introducing potassium carbonate into the water in relative amounts exceeding those used in the small-scale experiments did not result in a considerable additional reduction of the overpressures seen. In fact, pressures seem to increase slightly the more potassium carbonate was added. The moment of occurrence of the maximum overpressure was however delayed for increased amounts of potassium carbonate in the water indicating a reduction of combustion rates during the initial phases. The reason for this behaviour is not fully clear. According to Tam et al., 2003 approximately 25 % of droplets generated by a superheated water system are smaller than 20 µm and will be able to affect the flame speeds directly. This implies an effective mist concentration of 52 g/m^3 which is in the same range as the 30-80 g/m^3 used during the aqueous solution mist tests reported by Roosendans et al., 2017. Roosendans, 2018 points in the direction of the higher viscosity of the solution as a possible explanation. The higher viscosity may affect the droplet size distribution causing lower concentrations of fine droplets.

Secondly, an industrial water deluge system was applied. Again, both pure water and inhibitor-solutions were applied. In this case the explosion itself generates fine droplets due to water droplet break-up. At high water loads explosion peak pressures were reduced considerably by the water deluge but a clear effect of adding inhibitor to the water could not be differentiated between the deluge tests using pure water and those performed with inhibitor-solutions (See Figure 5). This may have been caused by the effect of initial turbulence generated by the water deluge system itself. This initial turbulence may be stronger when applying aqueous solutions of water and potassium carbonate due to the higher density of the solution. At lower water loadings, the mitigation effect of pure water was nearly negligible (considering the maximum explosion overpressure). For these low water loadings, however inhibitor-solutions were seen to have an effect. This is demonstrated in Figure 6 showing the maximum rate of pressure rise during the explosion tests for different water application rates (using pure water and a test where for a low application rate an aqueous solution of potassium carbonate and water was dispersed. The rate of pressure rise (an indication of the overall combustion rate) was considerably affected applying a low application rate with an aqueous solution of water and potassium carbonate compared to pure water.

The reason for this behaviour is not fully understood. An effect of higher viscosity due to higher solution concentration cannot explain the behaviour since instead the number of nozzles was reduced. Roosendans, 2018 argues that a balance situation would be reached where flame speeds cannot be reduced any further without losing the ability of breaking up droplets.

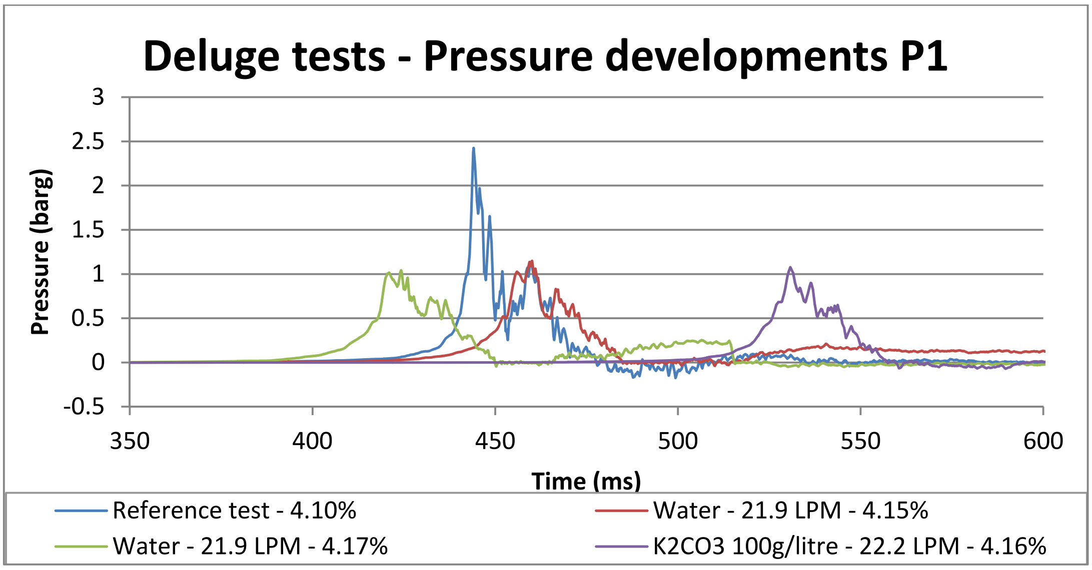

Figure 5: Effect of water deluge on overpressures generated by optimal propane-air explosions in a vented 50 m^3 obstructed chamber. The Figure shows a reference test (no water), two tests where water deluge was applied (water application rate 22 l/min/m^2) and a test where the same water application rate was used for a 100 g/l aqueous solution of potassium carbonate and water.

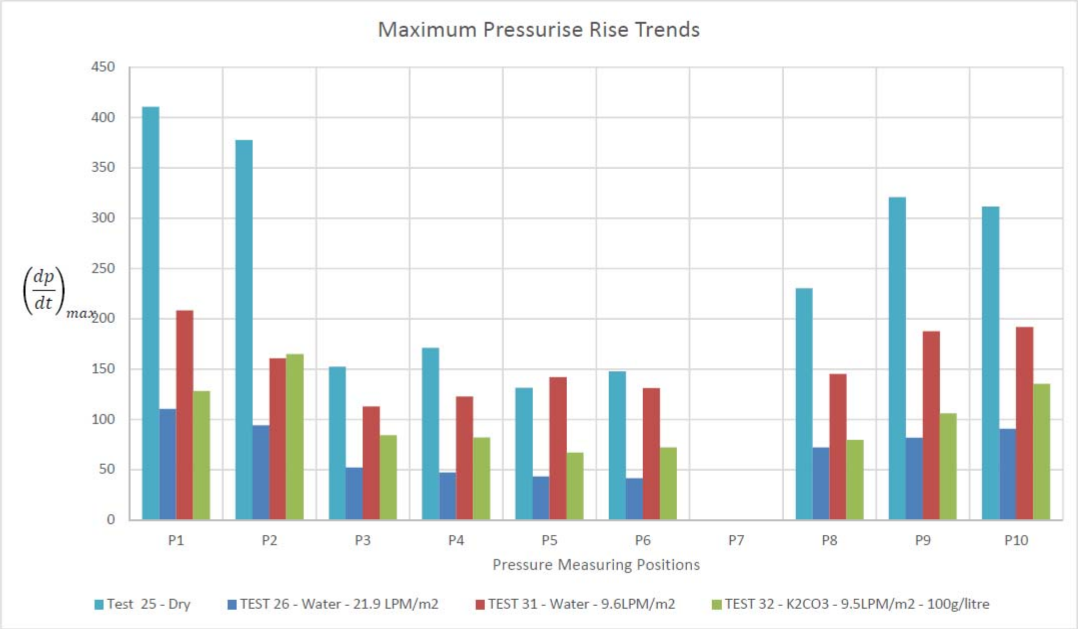

Figure 6: Effect of water deluge on the maximum rate of pressure observed during tests where optimal propane-air mixtures were ignited in a vented 50 m^3 obstructed chamber. The Figure shows a reference test (no water), a test where a high water application rate was used (water application rate 22 l/min/m^2), a test where a low water application rate was sued (9.5 l/ min/m^2) and a test where the same water application rate was used (9.5 l/min/m^2) for a 100 g/l aqueous solution of potassium carbonate and water.

4. Conclusions

Whereas direct injection of mists of aqueous solutions of water and potassium had considerable improved mitigation effects on explosions in a small-scale congested channel compared to injection of water mist only a similar effect could not be reproduced on a larger scale.

Generation of water mist using a superheated water injection system resulted in a considerable reduction of explosions overpressures in a congested 50 m^3 chamber when using pure water. This effect was however not improving any further when applying aqueous solutions of water and potassium carbonate. This might be related to the increased viscosity of the solution compared to water changing its dispersion properties.

Using a water deluge system instead, aqueous solutions were shown to have an improved mitigation effect on explosions compared to that of pure water when low application rates were used. Increasing the application rate aqueous solutions had no improved mitigation effect anymore.

Additional experimental work would be needed to understand this behaviour.

Acknowledgments

The authors acknowledge the financial support obtained from Total SA for performing these experiments.

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